A MAN-PORTABLE FOCUSED MICROWAVE PHASED ARRAY FOR HIGH-RESOLUTION IMAGING OF SHALLOW BURIED UXO

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Detection Technology - Microwave Imaging

Abstract

A major and costly problem in UXO detection and removal is the high false alarm rate of 90% or greater. Most sensors perform only a detection function and provide little or no information about the source of the detected anomaly. Consequently most detected objects must be manually excavated and removed, a very costly operation. A new developmental man-portable microwave sensor is described for high-resolution (1-cm) imaging of shallow UXO, buried to one-foot soil depth. The man-portable sensor will be a 1:4 scaled version of a successful prototype of a vehicular-mounted mine imaging system. The sensor is best used as a post-detection imaging system, i. e., it is used after a conventional metal detector has flagged a detected anomaly, to identify the buried object and determine if removal is required. The image of the object shows its shape and characteristic scattering signature that provides positive identification. The image also shows the exact object location and orientation, allowing safer removal. The sensor described is a rectangular microwave phased array formed by synthetic aperture principles, by the forward motion of a twenty-inch line array containing only eight antennas. The unique combination of polarization and propagation geometry minimizes surface reflections in moist soil. The rectangular array focuses a high-resolution receiving beam and scans throughout the subsurface volume of interest, forming a real-time color image on a laptop computer viewed by the operator. Because of the synthetic aperture formation using a simple line array, and parallel processing of the array elements in data acquisition software, the system is expected to be low cost. The system can form images in the horizontal plane and the two orthogonal vertical planes. Stereo images can also be formed by the combination of two sequential images during forward motion of the system. The presentation will show color images of buried objects at various depths in soil of varying moisture content, demonstrating the ability to discriminate among objects based upon shape, metallic composition, burial depth, and orientation.

BACKGROUND

The need for identification of buried objects that have been detected as possible UXO is vital. The amount of time spent investigating false alarms, as high as 99% of all detected targets, is extremely costly in terms of both dollars, and the psychological exhaustion of EOD experts who must uncover almost every detected anomaly. There is also a need for determining exactly the location and orientation of detected UXO to expedite safer removal.

There are several technologies that are available for detection, but few that can identify buried objects, much less determine their shape and orientation. This paper presents a technology that can do all of these, but is most efficiently used for identification by shape and orientation, after an anomaly has been detected by faster and more conventional means. The technology described is in the category of microwave imaging, and the means is the use a focused phased array antenna.

The range of depths of UXO is from above the ground surface to several meters. In almost all cases, the immediate threat is from UXO that is on the surface or at shallow depths down to about 1 foot. This is the UXO that presents the greatest hazard and is often found in public lands and recreational areas that were formerly used as artillery ranges. An example is Tobyhanna State Park in Pennsylvania, formerly Tobyhanna artillery range from World War I to World War II, where surface and shallow-buried shells had been found in and near the present family campground since 1995.

One of the primary difficulties in UXO removal operations is in the large number of non-ordnance items that are detected and removed. Most ordnance contains ferrous metal and most detection systems have sensitivity to ferrous objects, including non-ordnance objects. There are 100-1000 false alarms for every detected UXO. Most existing technologies for UXO operations perform only a detection function. Many sensors attempt to perform over a wide range of depths, so that there is a resulting large dynamic range in the received signals. There is also a wide range in the size of ordnance that must be detected, ranging in size from a few inches to a foot or more. Small shallow objects may give the same signal level as large deep objects, so signal strength cannot usually be used as a discriminator. Therefore there is often no way to discriminate desired buried ordnance from benign objects that give false alarms to the detectors.

Most ordnance is removed manually by trained explosive ordnance disposal personnel. Since this operation must be performed slowly and carefully, false alarm detections are very costly to the disposal operation. There is a great need for a method of reliably identifying detected buried objects so false alarms can be distinguished from real ordnance.

Another limitation of current operations is the inability to accurately determine the physical size and shape of buried ordnance to aid in its safe removal. The ability to determine the actual physical extent and orientation of buried explosive ordnance would assist greatly in its safe removal.

Thirdly, because of the often-ambiguous signal levels returned by many detectors, there is often little discrimination between shallow and deeper buried ordnance. Shallow buried ordnance presents the most immediate safety threat, especially in public areas. A system that discriminates shallow buried ordnance is needed.

The proposed microwave imaging system addresses all of these limitations for shallow buried ordnance. The system detects and images buried objects down to about a foot in typical soils. The system also forms an image with about a centimeter resolution, so the shape of shallow buried objects can be readily seen.

SYSTEM DESCRIPTION

The method presented in this paper for the identification of shallow buried UXO using microwave imaging has been determined both by need and technological necessity. The need has been established; the technological necessity derives from the limits of the physics in the ability to form high-resolution images using microwaves. There is a trade-off between the resolution and penetration depth of microwave detection or imaging systems. Both depend on the wavelength, and a smaller wavelength gives a higher resolution, but less penetration depth in the soil. The system described here has addressed the problem of high-resolution imaging of UXO to provide identification, and the depth of penetration is therefore limited. The frequency chosen is S-band, using a frequency of 3.5 GHz, which has a wavelength in soil of a couple of centimeters or so, depending on the soil type and moisture. This gives images with a resolution of a centimeter or two, but consequently limits the penetration depth to a foot or less, depending again on soil type and moisture content.

The system proposed here is a focused array microwave imaging system. It uses a two-foot line array of eight antennas that receive the radiation reflected from surface or subsurface objects that have been illuminated by a separate transmitter antenna. The line array samples this data at a sequence of eight forward positions during manual movement, forming a synthetic 64-element rectangular array covering a ground area of about 4 square feet. The data from these 64 antennas is processed in real-time to form a high-resolution focused beam in the near field of the array below the soil surface. The beam is scanned in one-centimeter increments in two dimensions to form a high-resolution image of the subsurface reflections and the image is presented in real-time on a notebook computer screen.

The system depends upon principles of propagation, reflection, and refraction of microwaves underground. It is not a ground-penetrating radar system since it does not use a pulse, and therefore avoids many of the limitations of radar. Some of the problems in microwave imaging which have been solved by this system are reflections from the ground which can obscure a subsurface signal, and achievement of a high resolution to identify buried objects by shape and orientation.

The system is illustrated in Fig. 1. An 8-element line array antenna is situated at the front and is pointed at an oblique angle toward the ground. It receives subsurface reflections from illumination provided by a transmitting horn antenna located at an equal and opposite oblique angle and pointed toward the ground between itself and the receiving array. The system is pushed forward on a wheeled cart by the operator. During the forward motion of the system, a single transmit-receive module receives the signals that are sequentially switched from the 8 antennas, and they are sampled by an A/D converter and stored in the system computer. This is repeated at equally spaced forward positions forming a 64-element synthetic rectangular array. The sampling of the data is performed in a data acquisition card in a laptop computer that performs the processing, focused near-field beamforming, and imaging. The image of the subsurface medium in a selected horizontal plane is shown on the laptop screen, and is updated in real time while the process continues as the system motion continues in the forward direction. The image is much like a CAT scan, in which the horizontal slice can be shown at any selected focus depth. It is expected that all the data collection and processing can be done in real time as the operator moves the system in a forward direction.

Because the detection depth is limited to about a foot, it appears that the system can best be used in conjunction with standard man-portable detection systems such as magnetometers or current meters as the primary detection devices. These devices will rapidly detect targets at depths to several feet, although they give only a gross approximation to target position, and little information about shape, size, or identification. After detection is made, if the suspect object is at a shallow depth, the detection can be confirmed, and the focused subsurface imaging system can provide an image for identification. In this manner, the most dangerous shallow buried ordnance can be efficiently detected and identified and flagged for removal. This is also a more cost effective solution since existing detectors would not need to be replaced, and only enough imaging systems would be required to image objects actually detected by the primary detection devices.

The technique uses a bistatic antenna system with transmitter and receiver located at the angles of incidence and reflection, respectively, of the radiation illuminating the ground. Furthermore, these angles are chosen equal to the Brewster angle of the ground medium, i. e., the angle at which only radiation having its polarization perpendicular to the plane of incidence is reflected. Consequently, if the antenna polarizations are in the plane of incidence, ideally all of the radiation will be transmitted into the ground and none will be reflected. After reflection from a buried object, the radiation will again be completely transmitted from the ground to air at the Brewster angle. Although this is a geometrical optics idealization in the presence of complex scattering phenomena in a partially conducting medium, the oblique propagation geometry significantly reduces surface reflections.

The transmitting antenna is an open-end waveguide, which illuminates the field of view on the ground. The receiver antenna is an 8-element horizontal line array of monopole antennas, perpendicular to the transmitting antenna axis. The entire system moves in the direction perpendicular to the horizontal line array, with the array sampling the reflected field at equal intervals in the direction of forward motion, forming a 64-element rectangular synthetic array. The array is focused in its near field, and the focal point is scanned in three dimensions below the surface of the ground. A high-resolution image is formed which will detect and identify buried objects, depending on their depth and dielectric contrast with the medium. The system uses a frequency of 3.5 GHz as a compromise between image resolution and soil attenuation.

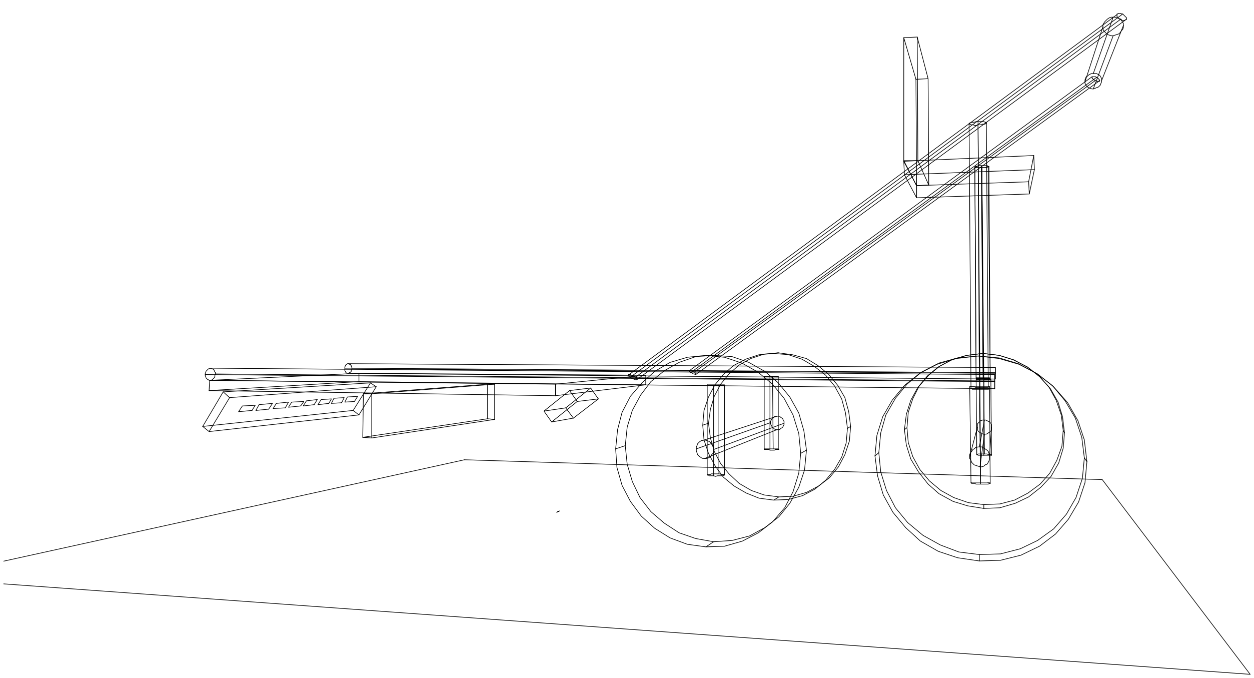


Fig. 1. Focused Array Subsurface Microwave Imaging System. The system is mounted on a lightweight, wheeled cart and pushed by an operator while he views on the laptop computer the real-time microwave image of the subsurface medium below the antennas. On the left is the 8-

element receiving antenna array and immediately ahead of the front wheels is the transmit horn antenna. Both antennas are pointed obliquely at the ground between them. The purpose of the system is to provide detection and high-resolution imaging of shallow buried objects to confirm detection and provide identification to reduce false alarms.

The geometry of the 8-element array system is illustrated in Fig. 2. The coordinate system shown has its origin on the ground directly below the transmitter. Depth is represented by the z coordinate, which increases with depth, while x increases toward the horizontal line array receiver and the y-axis is parallel to the line array. A bistatic antenna system is depicted which consists of a transmitter horn antenna with a wide beam, located at height h above the ground, for illumination of a large surface area, and a focused horizontal line array receiver at height h. Both are directed obliquely to a common area on the ground (x-y plane) below and between them. The oblique angle is chosen to be near the Brewster angle for the medium, i. e., the angle at which a wave polarized in the plane of incidence is completely transmitted into the medium. For this reason, the polarization chosen for the system is in the plane of incidence, the x-z plane. Although the beamwidth of the array elements covers a range of angles about the Brewster angle, and despite the medium being partially conductive, the proximity to the Brewster angle still results in a large reduction in surface reflections. Moist soil behaves like a dielectric in its reflective properties so there is still a large reduction in surface reflection for parallel polarization at angles near the Brewster angle. A conductive medium is also dispersive, which requires the use of a single frequency rather than a pulsed waveform to maintain reflected wavefront coherence across the array aperture.

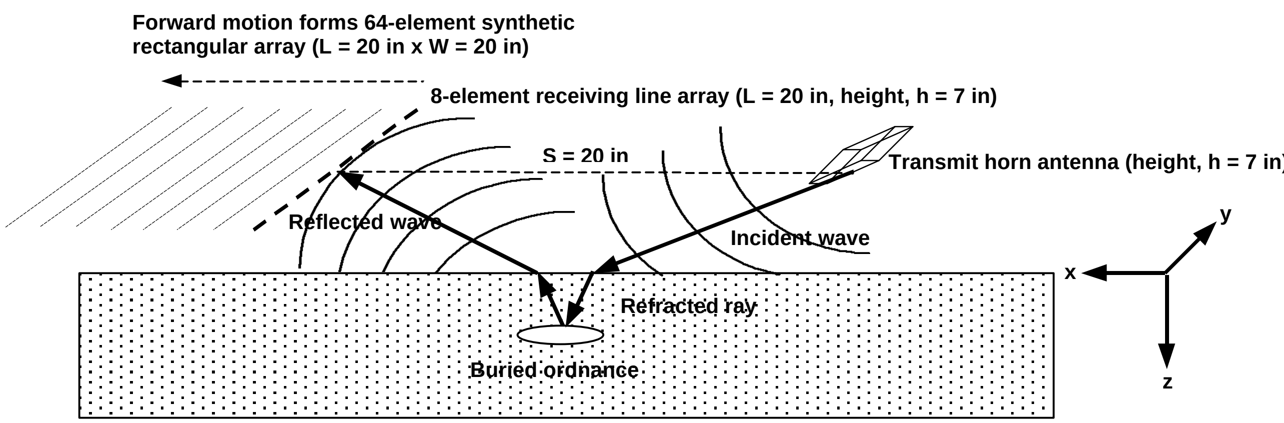


Fig. 2. Geometry of focused synthetic rectangular array system. A transmit horn antenna illuminates the ground at an oblique angle. The wave is refracted into the ground where it is reflected by buried objects, and the 8-element line array antenna receives the reflected wave. This is repeated for 8 forward positions of the line array, forming a synthetic 64-element rectangular array. A two-dimensional horizontal image of a buried object is then formed by the rectangular array from the stored data by focusing and scanning over the area illuminated. The real-time image is continuously updated as the array continues its forward motion, giving a scrolling two-dimensional image of the subsurface medium. S = 20 in. is the separation between transmitter and receiver antennas; h = 7 in. is the transmitter and receiver antenna height; L = 20 in. is the 8-element array length; and W = 20 in is the width of the synthetic rectangular phased array receiving antenna which has dimensions L x W.

EXPERIMENTAL RESULTS

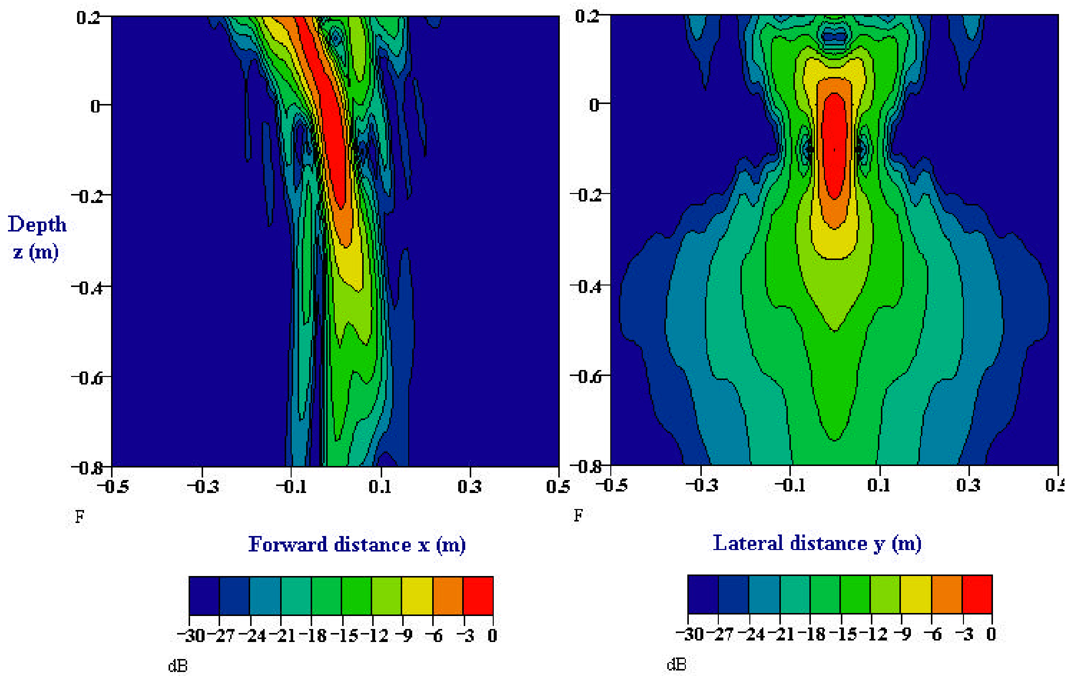
The man-portable microwave imaging system uses the same technology, and is 1/4 the scale of the successful vehicular-mounted prototype that was used to image buried objects. Because spatial resolution is proportional to the ratio of distance to array length, the resolution ability of the man-portable system will be identical to the vehicular-mounted prototype. The expected results of the developmental man-portable imaging system therefore can be predicted from those obtained with the vehicular-mounted system that will be presented here. Although the vehicular-mounted system was developed for mine detection, images are presented here which indicate the ability to image metallic UXO.

The horizontal line array consisted of vertically polarized balun-fed dipole elements a quarter wavelength above a ground plane, and spaced at 0.775 wavelengths. The elements were sequentially switched into a single T/R module, which maintained signal coherence and provided baseband I and Q components of the array element signals. The forward motion of the array formed a synthetic aperture at sequential forward positions resulting in a rectangular array.

Fig. 3 shows contour plots of the calculated focal region beam of the synthetic rectangular array formed by the motion of the transmitter and receiving line array system. The array is focused in the Fresnel region at the longitudinal midpoint of the system at a depth of 10 cm, which is near the depth of most of the buried objects. The contours show the side and front views of the pattern. The horizontal beam cross-section is circular with a diameter of 5 cm.

The experiments were performed in a sand medium, with water added as a percentage of dry weight. The tests used dry sand, 5% and 10% water by dry weight (7.3% and 14.6% by dry volume, respectively). Objects were buried at depths of 7.5 cm. Beams were formed every centimeter over an 80-cm x 80-cm area for a total of 6400 beams. The image of the sand in the absence of buried objects was used as the reference. The images are in the horizontal x-y plane at the buried object depth.

Figs. 4-9 show images of selected objects over an 80-cm x 80-cm area in the x-y plane at the focus depth of 7.5 cm. The images selected are of metallic objects of various shapes to demonstrate the ability to identify UXO by shape. The images are quantized into 80 color levels relative to the image peak. Each image pixel corresponds to a 1-cm x 1-cm beam location. A template of the object shape is superimposed on each image. The soil dielectric constant is ε, the conductivity is σ, the depth is d, and the maximum signal level in the image is given in volts. Also given is the signal-to-clutter ratio as S+C/C. Figs. 4-6 are of an M15 metal anti-tank mine, each with different soil moisture content. It has distinctive shape features that can be used for identification in each case. The dry soil result of Fig. 4 shows a characteristic shape and scattering pattern that depends upon the different heights of different parts of the mine. Edges show prominently because of the interference of reflections from the two heights at the edge. The signal-to-clutter ratio exceeds 22 dB. The edges appear differently in Figs. 5 and 6, as moisture content is increased to 5% and 10%, because of the different dielectric constant, and hence wavelength, in the soil, causing different phase interference at the edges. The observed signal-to-clutter ratio also decreases as moisture content increases because of the increased attenuation of the signal, and increased soil surface reflections. It is apparent that the system provides a resolution of about 1 or 2 cm and is able to actually image the objects for positive identification. Figs. 7 and 8 show the ability to distinguish objects by shape, showing the images of a cylindrical and rectangular can, respectively, which closely match their templates. The signal-to-clutter is about 20 dB in both cases. Fig. 9 demonstrates the imaging capability for water, which actually behaves as both dielectric and conductor. A plastic 2-liter bottle filled with water was buried and the image was formed. Notable is the ability to image the actual shape of the water bottle showing the neck and top. Other results not shown are images of additional dielectric objects such as rocks and plastic, showing their shape and position accurately. These results show the ability of an S-band microwave phased array to detect, image and identify both conducting and dielectric buried objects.



(a) *(b)*

Fig. 3. Focused near-field array patterns of synthetic rectangular array focused at 10 cm below the soil surface. The soil surface is at z=0. (a) side view of subsurface array pattern showing x-z plane; (b) front view of subsurface array pattern showing y-z plane.

BIOGRAPHY AND BIBLIOGRAPHY

William J. Graham received the Ph. D. in Electrical Engineering and Science from the Moore School of Electrical Engineering, University of Pennsylvania in 1979. He has had antenna experience with GE, Department of the Navy, RCA, and Lockheed-Martin. He is now president of Graham Research Corporation, specializing in antenna systems development, especially using phased array technology, and applications to focused array subsurface imaging.

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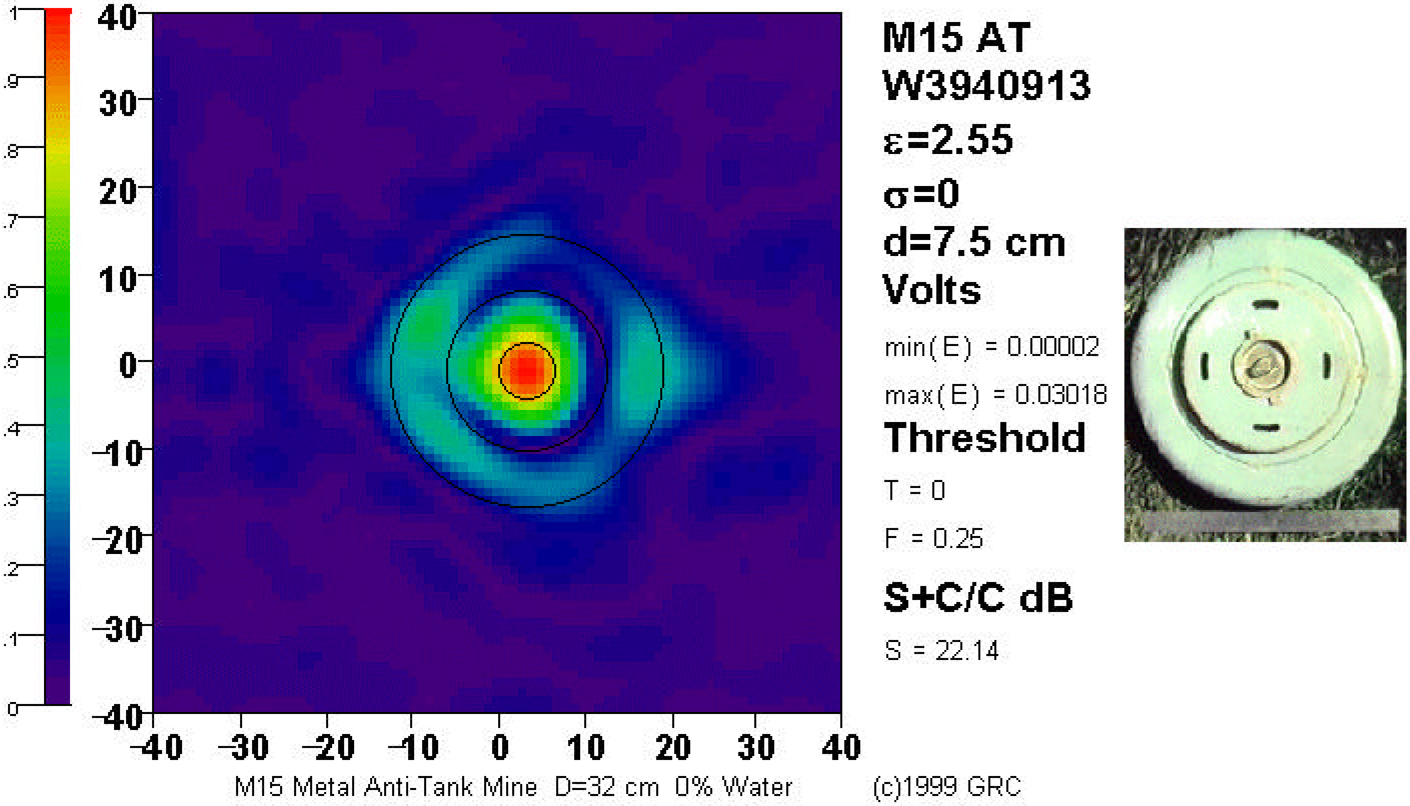

Fig. 4. M15 in dry soil shows distinct edges that correspond closely to photo on right.

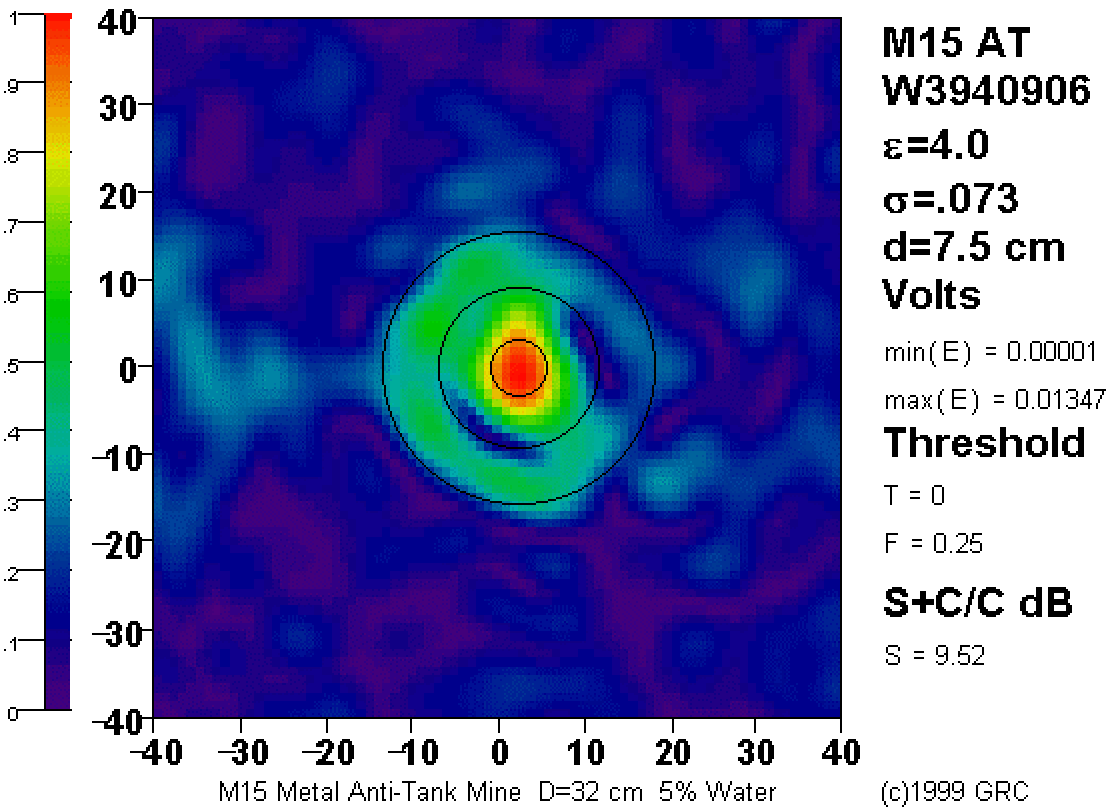

Fig. 5. Soil with 5% water gives variation in image, still identifiable with lower S/C.

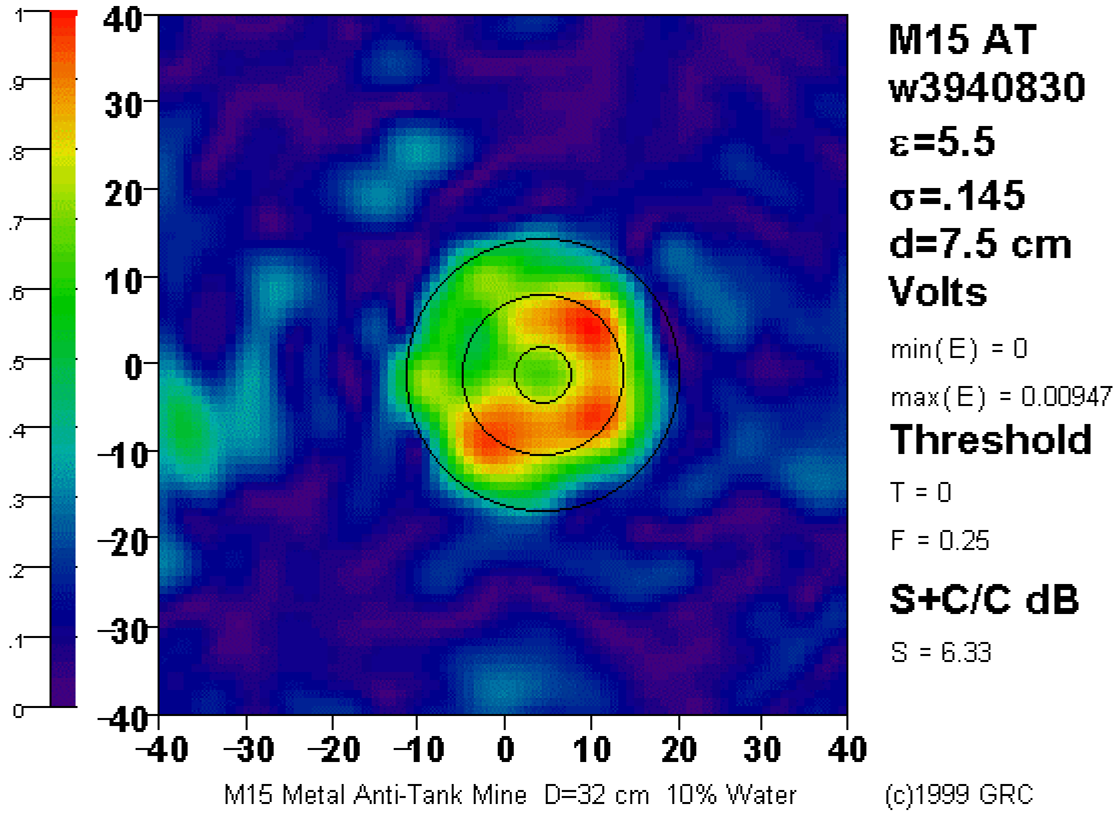

Fig. 6. 10% water content changes edge interference but shape and features identifiable.

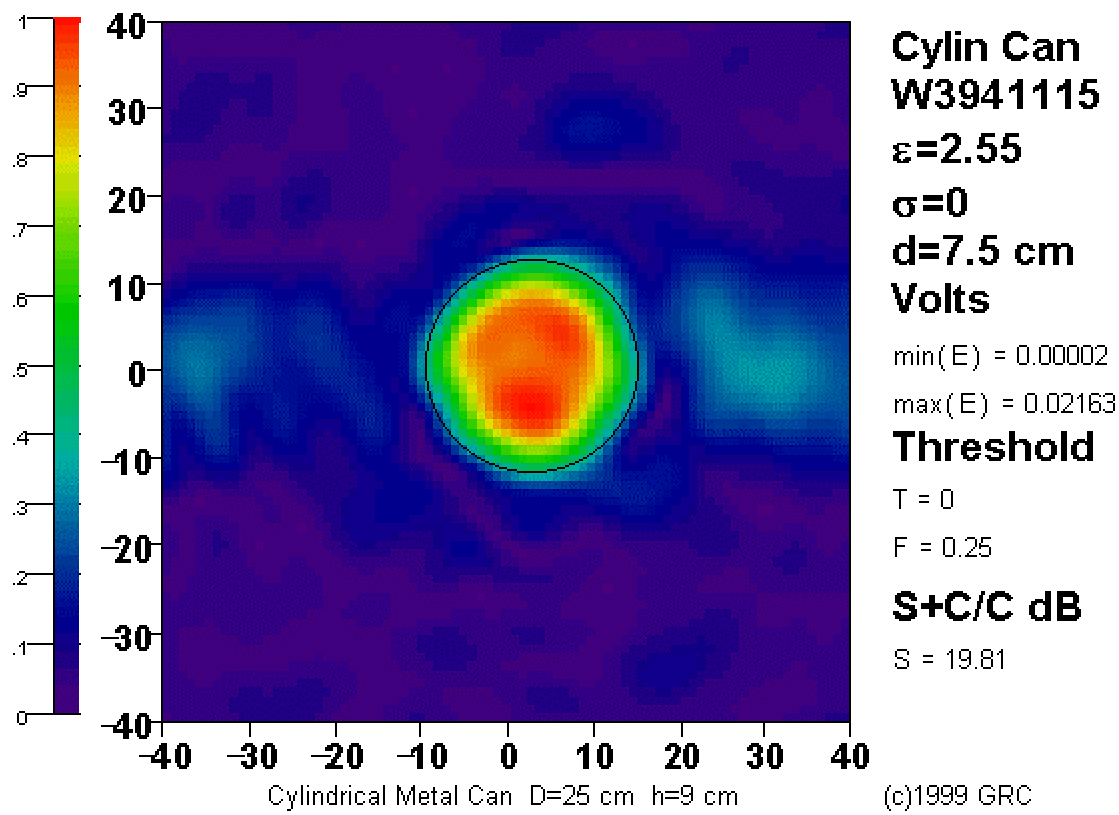

Fig. 7. Shape of cylindrical metal can buried in dry soil exactly matches template.

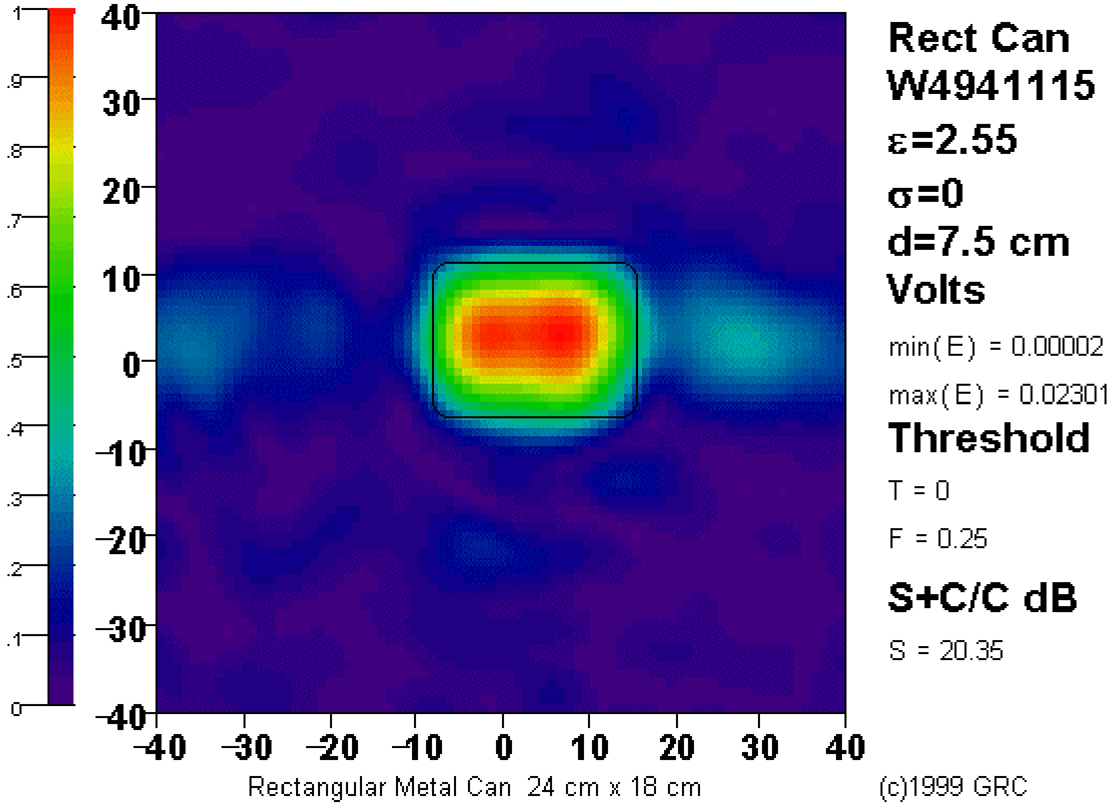

Fig. 8. Shape of rectangular metal can is easily distinguishable from round can.

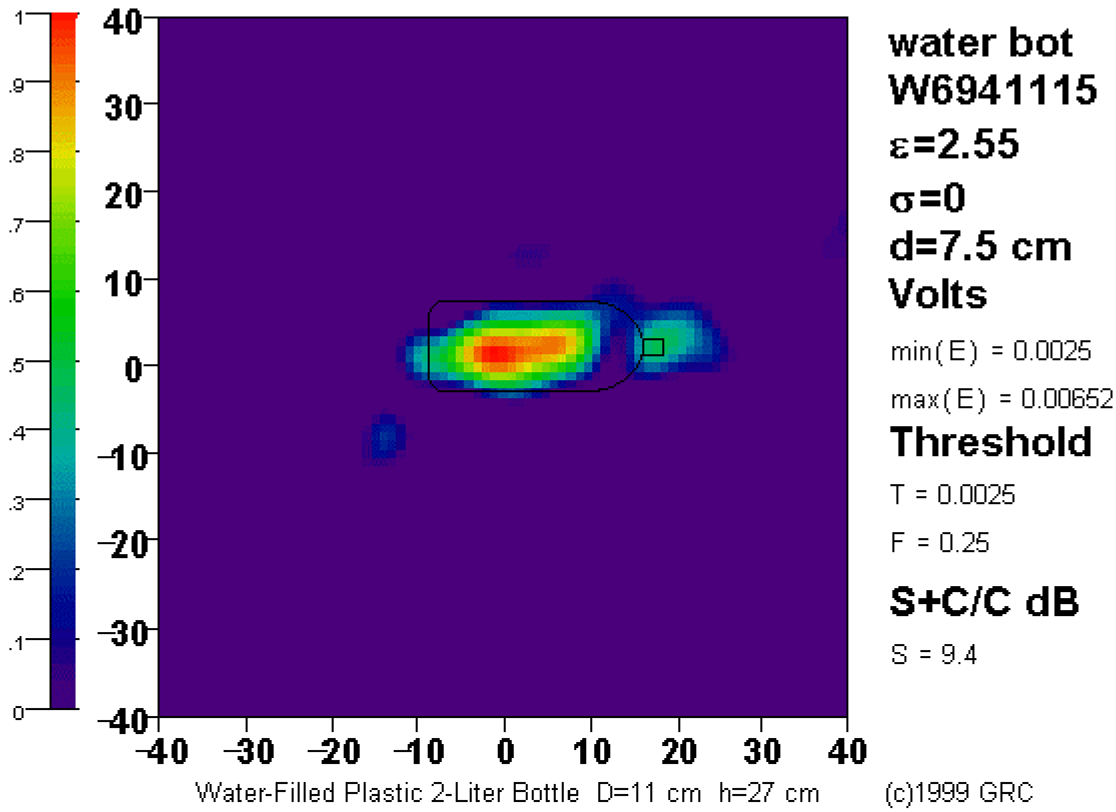

Fig. 9. Image of water-filled bottle and top are identifiable in dry soil.